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Fundamental Properties and Practical Application of Active Microwave Metamaterials Incorporating Gain Devices

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14. ABSTRACT
Metamaterials are artificially designed composite materials which can exhibit unique and unusual properties such as the negative refractive index, negative phase velocity, etc. The concept of metamaterials becomes prevalent in the electromagnetic society since the first experimental implementation in the early 2000s. Many fascinated potential applications, e.g. super lens, invisibility cloaking, and novel antennas that are electrically small, have been proposed based on metamaterials. However, most of the applications still remain in theory and are not suitable for practical applications mainly due to the intrinsic loss and narrow bandwidth (large dispersion) determined by the fundamental physics of metamaterials.
In this program, we have incorporated active gain devices into conventional passive metamaterials to overcome loss and even provide gain. Two types of active gain negative refractive index metamaterials have been proposed, designed and experimentally demonstrated, including an active composite left-/righthanded transmission line and an active volumetric metamaterial. These designs have been extended to THz frequency range. In addition, we have investigated the non-Foster circuits for broadband matching of electrically small antennas. A rigorous way of analyzing the stability of non-Foster circuits by normalized determinant function has been proposed. We have studied the practical factors that may affect the stability of non-Foster circuits, including the device parasitics, DC biasing, layouts and load impedance. A stable floating negative capacitor has been designed, fabricated and tested. Moreover, it is important to resolve the sign of refractive index for active gain media which can be quite challenging. We have investigated the analytical solution of a gain slab system, and applied the Nyquist criterion to analyze the stability of a causal gain medium. W

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Final Report - Fundamental Properties and Practical Applications of Active Microwave Metamaterials Incorporating Gain Devices

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In this program, we have studied the potentials and challenges of utilizing active gain device and non-Foster element to overcome the loss and bandwidth limits on conventional passive MTMs and electrically small antennas. First, we have investigated the theoretical limits on the loss and dispersion of passive MTMs. It can be proved that a passive NIM cannot be completely lossless and non-dispersive. The theoretical limits on the loss and dispersion of passive MTMs are reviewed. Our research has clearly demonstrated both theoretically and experimentally that the loss of a MTM can be compensated by judiciously placing the active gain device, e.g. TD, into a MTM unit cell. Over-compensation (gain) is achieved without losing the unique property of negative refractive index. Two types of active gain NIMs including an active CLRH TL and an active volumetric MTM are proposed, designed, and experimentally verified. Both have shown the simultaneous negative refractive index with gain. Figures 1 and 2 show the results of the volumetric active MTM that has negative index of refraction as well as gain simultaneously.

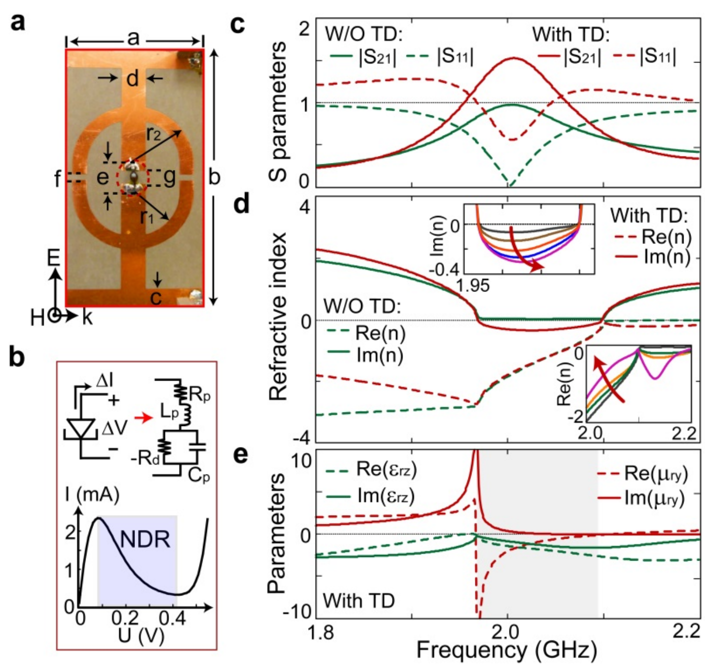

Figure 1. Simulated results and retrieved parameters of the sub-wavelength wire and SRR based artificial medium with and without embedded TDs. (a) Photograph of the fabricated unit cell with an embedded TD. Metallic patterns are printed on a 1.27-mm-thick Rogers-6006 substrate, whose dielectric constant is 6.5. Related dimensions are a = 27 mm, b = 54 mm, c = 4 mm, d = 5 mm, e = 6 mm, f = 0.8 mm, g = 2.5 mm, r_1 = 9 mm, and r_2 = 12 mm. (**b**) Equivalent circuit model of the embedded TD (TD261 by General Electric) and its I-V curve. R_p, L_p and C_p are the parasitic resistance, inductance and capacitance of the TD, respectively (**c**) Simulated *S* parameters of the unit cell with and without the TD under a normal plane wave incidence. The polarization of the incidence is shown at the bottom left corner of (a). (d) Retrieved effective refractive index of the effective medium with and without TD. The upper and lower insets show the dependency of the real and imaginary parts of retrieved refractive index on $-R_d$. As indicated by the red arrows, with an increased R_d, while the imaginary part of the refractive index becomes more negative, the real part becomes less negative. (**e**) Retrieved constitutive parameters of the effective medium with embedded TD.

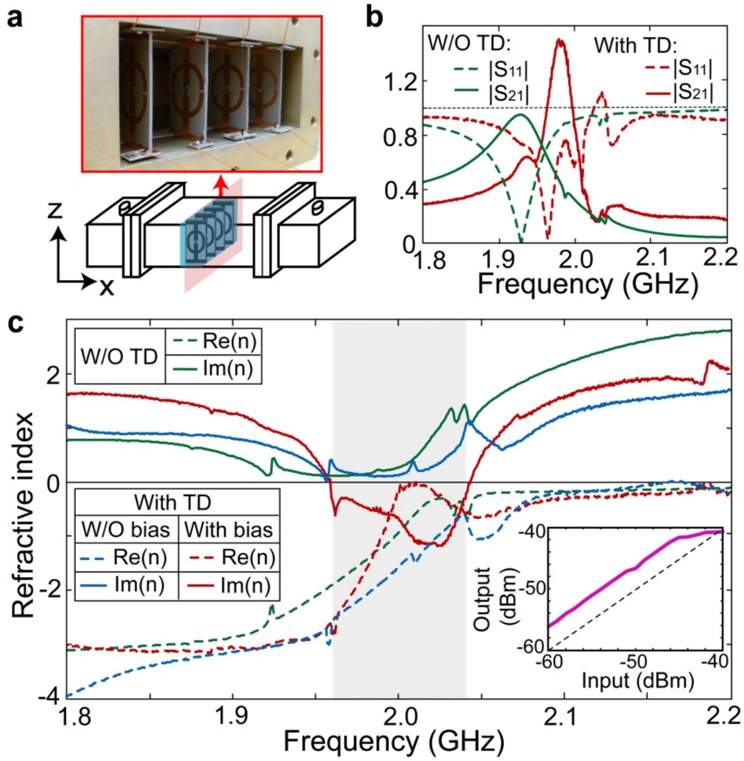

Figure 2. Experimental results and retrieved parameters of the fabricated metamaterial sample. (a) Photograph (top) and schematic drawing (bottom) of the fabricated single layer sample placed in a standard WR-430 rectangular waveguide. (b) Measured *S* parameters for the samples without TDs (green lines) and with TDs biased at a DC voltage of 0.38 V (red lines). The *S* parameters were measured using a vector network analyzer, i.e., Agilent E8361a. (c) Retrieved refractive indices from the experimental *S* parameters for three different configurations, i.e., the sample without TDs (green lines), the sample with unbiased TDs (blue lines) and the sample with biased TDs (red lines). The inset shows the dependency of the output power on the input power. It is seen that in a wide range of incident power, the gain remains stable.

The problem of sign ambiguity of active gain metamaterial is then investigated theoretically. Based on the Nyquist criterion, we have analyzed the stability of a gain slab system made of different dispersive gain media. Two methods for determining the sign of refractive index for general lossy and gain media are developed and compared. We have also investigated a 45° wedge example to illustrate the frequency-domain simulation must be treated with care. The potential instability cannot be observed from the numerical simulation result.

Moreover, we have investigated the non-Foster circuits for broadband matching of electrically small antennas. We have proposed a rigorous way of analyzing the stability of non-Foster circuits by normalized determinant function (NDF) method. A stable floating negative capacitor has been designed, fabricated and measured. We have studied practical factors that may affect the stability of non-Foster circuits. The factors include the device parasitics, the choice of DC biasing, the length of TLs in the layout, and the realistic load impedance. The concept of non-Foster element, such as the negative capacitor and negative inductor, is then introduced to improve the matching bandwidth of electrically small antennas. A negative-resistor NII circuit and Linvill NIC circuit are used to realize non-Foster elements, however, the non-Foster elements are shown to be bandwidth-limited in practice. Experiments have been done to verify the stability analysis results. By carefully design of the non-Foster circuit, we then achieved a stable negative capacitor in practice. A -40 pF non-Foster circuit is then applied to match a 2-meter helical antenna at HF band. The result shows that the non-Foster matched helical antenna received 20-30 dB more signal power from 3 to 13 MHz than without matching case, and 15 dB more than commercial HF whip antenna.

In the future works, with the proof of the existence of active gain NIMs in practice, one can study its potential applications by taking advantages of its unique properties. By a deep understanding of the behavior of gain MTMs at microwave frequencies, one may scale down the size and build up active gain MTMs at THz or optical frequencies, which have more severe material losses than microwave frequencies. Such active MTMs can help realize novel device, such as active antennas, nanoscale or cavity-free lasers, active imaging, etc.

Another interesting topic to work on is the nonlinear active MTM. The large enhancement of nonlinear effects has been observed in many nonlinear active MTMs, which is not common in ordinary nonlinear optical media. Various specific and novel phenomena are also predicted or observed in nonlinear active MTMs, including bistability, tuning and switching, nonlinear chirality, frequency conversion and parametric amplification, phase matching and phase conjugation, etc.

Although we have proved the benefit from non-Foster matching circuit for electrically small antennas, there are still many challenges in this area. For example, we have only proposed the method of analyzing the stability, however, there are still no definite design rules showing how to stabilize the active circuit without sacrificing the performance. A synthesis method of non-Foster network also needs to be developed. In addition, for practical communication application, the power capacity and the DC-power consumption of the non-Foster matching circuit need to be taken into consideration for a transmit antenna. At the receiver end, the noise figure of the non-Foster matching circuit also needs to be considered.

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Abstract

Metamaterials are artificially designed composite materials which can exhibit unique and unusual properties such as the negative refractive index, negative phase velocity, etc. The concept of metamaterials becomes prevalent in the electromagnetic society since the first experimental implementation in the early 2000s. Many fascinated potential applications, e.g. super lens, invisibility cloaking, and novel antennas that are electrically small, have been proposed based on metamaterials. However, most of the applications still remain in theory and are not suitable for practical applications mainly due to the intrinsic loss and narrow bandwidth (large dispersion) determined by the fundamental physics of metamaterials.
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